ALDOT-395-1999
STONE MATRIX ASPHALT MIX DESIGN

1. Scope

1.1. This procedure covers the design of stone matrix asphalt (SMA) using either the gyratory compactor or the Marshall hammer. The design is based on the volumetric properties of the SMA including air voids, voids in the mineral aggregate, stone on stone contact, and mortar properties.

2. Referenced Documents

2.1. AASHTO Standards

2.1.1. AASHTO T-19, Standard Method of Test for Bulk Density (Unit Weight) and Voids in Aggregate.

2.1.2. AASHTO T-27, Standard Method of Test for Sieve Analysis of Fine and Coarse Aggregates.

2.1.3. AASHTO T-84, Standard Method of Test for Specific Gravity and Absorption of Fine Aggregate.

2.1.4. AASHTO T-85, Standard Method of Test for Specific Gravity and Absorption of Coarse Aggregate.

2.1.5. AASHTO T-305, Standard Test Method for Determination of Draindown Characteristics in Uncompacted Asphalt Mixtures.

2.2. ALDOT Documents

2.2.1. Materials, Sources, and Devices with Special Acceptance Requirements Manual.

2.2.2. ALDOT-307, Design Method for Selecting Optimum Asphalt Cement Con-tent of Hot-mix Asphalt by Means of the Marshall Apparatus.

2.2.3. ALDOT-361, Resistance of Compacted Hot-mix Asphalt to Moisture Induced Damage.

2.2.4. ALDOT-384, Mix Design Procedure for Superpave Level 1.

2.2.5. Alabama Department of Transportation Standard Specifications for Highway Construction.

3. Definitions and Nomenclature

3.1. Stone matrix asphalt (SMA): SMA is hot-mix asphalt consisting of two parts - a coarse aggregate skeleton and an asphalt-rich mortar. The aggregate skeleton must have stone on stone contact and the liquid asphalt must possess good rheometric properties as given in Section 804 of the Alabama Department of Transportation Standard Specifications for Highway Construction.

3.2. SMA mortar: The mixture of polymerized liquid asphalt binder, mineral dust (mineral filler), and fiber.

3.3. Voids in the coarse aggregate (VCA): The volume in between the coarse aggregate particles. This volume includes the mineral filler, the fine aggregate, air voids, polymerized liquid asphalt binder, and fiber.

3.4. RAP: recycled asphalt pavement.

3.5. RAS: reclaimed asphalt shingles.

4. Procedures

4.1. Determine if the mix is for a wearing layer. Select an aggregate structure (gradation) and performance grade liquid asphalt binder based upon the Alabama Department of Transportation Standard Specifications for Highway Construction, plans, and proposal.

4.2. Select fine and coarse aggregates from the Alabama Department of Transportation approved sources (see Materials, Sources, and Devices with Special Acceptance Requirements Manual, List I-1) and select a mineral filler that meets the specifications.

4.3. Use of RAP and RAS is allowed as per Section 410.02 of the Alabama Department of Transportation Standard Specifications for Highway Construction.

4.4. Dry the aggregates to a constant weight (mass) at approximately 230°F (110°C) and separate them into the following size fractions:

1 1/2 to 1"	(37.5 to 25.0 mm)
1 to 3/4"	(25.0 to 19.0 mm)
3/4 to 1/2"	(19.0 to 12.5 mm)
1/2 to 3/8"	(12.5 to 9.5 mm)
3/8" to No. 4	(9.5 to 4.75 mm)
No. 4 to No. 8	(4.75 to 2.36 mm)
Passing No. 8	(2.36 mm)

4.5. Combine the aggregates in a blend that falls within the master ranges specified. These ranges are based on percent passing by volume. These gradations based on volume are converted to weight (mass) for mixture design and control. It is recommended that at least three trial blends be evaluated.

4.6. In general, the mixing temperature is the temperature where the liquid asphalt binder has a viscosity of 170 ± 20 cSt and the compaction temperature is the temperature where the liquid asphalt binder has a viscosity of 280 ± 30 cSt; however, since the liquid asphalt binder contains polymer, the mixing and compaction temperatures may be different, so the manufacturer's recommendations and guidelines should be followed to determine mixing and compaction temperatures.

4.7. Using a mechanical mixer, an initial batch shall be mixed to coat the mixing bowl and stirrers (this is usually referred to as "buttering"). This batch shall be emptied after mixing and the sides of the bowl and stirrers scraped clean with a limber spatula. Do not clean the bowl and stirrer with solvents unless the liquid asphalt binder or aggregate source is changed (in which case, re-butter the bowl and stirrers).

4.8. Weigh into separate containers for each test specimen the amount of each size fraction required to produce a batch of aggregate that will result in a compacted specimen of the correct size. For Marshall compaction this is 2 1/2" (63.5 mm) and approximately 1200 grams. Up to four Marshall specimens may be batched at once, but care must be taken not to segregate the mixture. For Superpave compaction this is 4 1/2" (115 mm) and approximately 4500 grams. The amount of aggregate in each batch shall be adjusted to produce compacted specimens of the correct height (within 5 percent is usually accurate enough). Mix the aggregate in each container and place them in an oven and heat per the mixing temperatures established in section 4.6. Heat the liquid asphalt binder to the mixing temperature. The stabilizing fiber shall be added to and mixed with the aggregates prior to the addition of the liquid asphalt binder. If the fiber is not thoroughly mixed with the aggregate prior to the liquid asphalt binder, the fiber will clump and the results will be invalid.

4.9. Form a crater in the dry blended aggregate and fiber and pour into the crater the required amount of liquid asphalt binder. At or above the mixing temperature, mix the aggregate, liquid asphalt binder, and fiber until the aggregate and fiber are thoroughly coated.

4.10. Age and compact the specimens according to ALDOT-307 (Marshall) or ALDOT-384 (Superpave) and the specifications. Use the procedures in ALDOT-307 (Marshall) or ALDOT-384 (Superpave) to determine the optimum asphalt content for each trial blend. SMA mixes shall be designed using a 50 blow Marshall design or 60 gyrations if using Superpave gyratory compactor.

4.11. Evaluate the trial blends for air voids (Va) and voids in the mineral aggregate (VMA) using the equations in ALDOT-307 (Marshall) or ALDOT-384 (Superpave). Evaluate the trial blends for voids in the coarse aggregate of the mix (VCA_{MIX}) using the equations found in Section 6, Examples, in this procedure.

4.12. Evaluate the tensile strength ratio (TSR) and drain down properties of the best trial gradation at the optimum asphalt content using ALDOT-361 and AASHTO T 305.

Note: It may be difficult to obtain more than 7 percent Va for the TSR test; as long as the Va is equal to or greater than 6 percent the results will still be valid.

5. Mixture Adjustments

5.1. The air void content may be adjusted by changing the asphalt content. If changing the asphalt content drops the VMA or asphalt content below the minimum in the specifications, the air voids must be adjusted by changing the gradation.

5.2. The VMA may be raised by increasing the percentage of coarse aggregate. Changing the aggregate source may also help raise VMA.

5.3. The VCA_{MIX} may be lowered by changing the gradation (typically by increasing the percentage of coarse aggregate) or by changing the aggregate source.

5.4. The drain down may be lowered by increasing the amount of fiber used or by changing the source of the fiber.

6. Examples

6.1. Percent Passing By Volume: With SMA the specific gravities of different aggregate components are not always similar enough to blend based upon weight (mass); this is especially true when comparing mineral fillers to the other aggregates. Therefore, SMA gradation bands are based upon percent passing by volume. If the bulk specific gravities of the different aggregates (including the mineral filler) vary by less than 0.025, gradations based on weight (mass) may be used.

6.2. Perform gradation testing by AASHTO T-27. Determine the bulk specific gravity of the aggregates by AASHTO T-84 and T-85. Table 1 gives the results.

Table 1

Sieve Size	Percent Passing Based Upon Weight (Mass) and Bulk Specific Gravity			
	Aggregate A	Aggregate B	Aggregate C	Mineral Filler
1" (25 mm)	100.0	100.0	100.0	100.0
3/4" (19 mm)	95.0	100.0	100.0	100.0
1/2" (12.5 mm)	66.0	71.0	97.4	100.0
3/8" (9.5 mm)	43.0	46.0	84.6	100.0
# 4 (4.75 mm)	9.0	6.0	48.9	100.0
# 8 (2.36 mm)	5.0	4.5	27.8	100.0
# 16 (1.18 mm)	2.9	4.0	16.6	100.0
# 30 (0.60 mm)	2.5	3.4	10.7	100.0
# 50 (0.30 mm)	2.0	3.0	7.6	96.0
# 100 (0.15 mm)	1.5	2.5	6.5	83.0
# 200 (0.075 mm)	1.0	1.5	4.6	72.5
Gsb	2.616	2.734	2.736	2.401

6.3. The second step is to determine the percent by weight (mass) retained on each individual sieve. For a given sieve this is calculated by subtracting the percent passing the given sieve from the percent passing the next larger sieve. For example, the percent retained on the No. 4 (4.75 mm) sieve for aggregate A is (43 - 9) = 34. This is not a cumulative weight (mass) retained, it is the weight (mass) retained on the individual sieve. Table 2 shows the percent by weight (mass) retained for each individual sieve. The calculations may be checked by totaling each column to 100.

Table 2

	Percent by Weight (Mass) Retained for Each Individual Sieve			
Sieve Size	**Aggregate A**	**Aggregate B**	**Aggregate C**	**Mineral Filler**
1" (25 mm)	0.0	0.0	0.0	0.0
3/4" (19 mm)	5.0	0.0	0.0	0.0
1/2" (12.5 mm)	29.0	29.0	2.6	0.0
3/8" (9.5 mm)	23.0	25.0	12.8	0.0
# 4 (4.75 mm)	34.0	40.0	35.7	0.0
# 8 (2.36 mm)	4.0	1.5	21.1	0.0
# 16 (1.18 mm)	2.1	0.5	11.2	0.0
# 30 (0.60 mm)	0.4	0.6	5.9	0.0
# 50 (0.30 mm)	0.5	0.4	3.1	4.0
# 100 (0.15 mm)	0.5	0.5	1.1	13.0
# 200 (0.075 mm)	0.5	1.0	1.9	10.5
Pan (-0.075 mm)	1.0	1.5	4.6	72.5
Total (∑)	100	100	100	100

6.4. Because each column totals to 100 percent, we can assume 100 g of each aggregate source and know that the amount in grams retained on each individual sieve is equal to the percent retained on each individual sieve. Using this information and the aggregate's bulk specific gravity we can calculate the volume of aggregate on each individual sieve

6.5. The volume of aggregate retained on each individual sieve can be determined from the following equation:

$$\text{volume of aggregate retained} = \frac{\text{mass of aggregate retained in grams on each individual sieve (cm}^3\text{)}}{\text{specific gravity of aggregate} * \gamma w}$$

where γw is the unit weight of water (in g/cm^3).

6.6. The following shows how the volume is calculated for the aggregate retained on the No. 4 (4.75 mm) sieve for aggregate C.

$$\text{Volume} = 35.7 \text{ g} / (2.736 * 1 \text{ g/cm3}) = 13.05 \text{ cm}^3$$

6.7 The volume for all sieves is shown in Table 3.

Table 3

	Volume Retained on Each Individual Sieve			
Sieve Size	**Aggregate A**	**Aggregate B**	**Aggregate C**	**Mineral Filler**
1" (25 mm)	0.0	0.0	0.0	0.0
3/4" (19 mm)	1.91	0.0	0.0	0.0
1/2" (12.5 mm)	11.09	10.61	0.95	0.0
3/8" (9.5 mm)	8.79	9.14	4.68	0.0
# 4 (4.75 mm)	13.00	14.63	13.05	0.0
# 8 (2.36 mm)	1.53	0.55	7.71	0.0
# 16 (1.18 mm)	0.80	0.18	1.09	0.0
# 30 (0.60 mm)	0.15	0.22	2.16	0.0
# 50 (0.30 mm)	0.19	0.15	1.13	1.67
# 100 (0.15 mm)	0.19	0.18	0.40	5.41
# 200 (0.075 mm)	0.19	0.37	0.69	4.37
Pan (-0.075 mm)	0.38	0.55	1.68	30.20
Total (∑	38.22	36.58	36.54	41.65
Gsb	2.616	2.734	2.736	2.401

6.8 The values provided in Table 3 are used to blend the different stockpiles to meet the desired gradation based on volumes. In this procedure the aggregate is blended by weight (mass), and then the gradation based on volume is determined. This is a trial and error process. To perform the blending, select the estimated percentages by weight (mass) of the different stockpiles to be used. For this example, the following percentages will be tried first.

Stockpile	**% Blend by Weight (Mass)**
Aggregate A	30
Aggregate B	30
Aggregate C	30
Mineral Filler	10

6.9 The percentages above are based on weight (mass). This indicates that the volume represented by 30 percent by weight (mass) of aggregate A will be used in blending the stockpiles based on volumes. The percent of each stockpile in the blend is multiplied by the volume retained on a given sieve for each stockpile to determine the total volume retained on that sieve. For the No. 4 (4.75 mm) sieve, using the volumes from Table 3 and the above percentages, the total volume retained on the No. 4 (4.75 mm) sieve is calculated as follows:

$$\text{Total Volume Retained} = (0.3 * 13.00) + (0.3 * 14.36) + (0.3 * 13.05) + (0.1 * 0.0) = 12.20 \text{ cm}^3$$

6.10 This calculation is performed for each sieve in the gradation. Table 4 shows the volume retained for each sieve in the gradation.

Table 4

Sieve Size	**Volume Retained per Sieve, cm^3**
1" (25 mm)	0.00
3/4" (19 mm)	0.57
1/2" (12.5 mm)	6.80
3/8" (9.5 mm)	6.78
# 4 (4.75 mm)	12.20
# 8 (2.36 mm)	2.31
# 16 (1.18 mm)	1.52
# 30 (0.60 mm)	0.76
# 50 (0.30 mm)	0.61
# 100 (0.15 mm)	0.77
# 200 (0.075 mm)	0.81
Pan (-0.075 mm)	3.80
Total (∑)	36.93

6.11 Now, based on the total volume retained per sieve and the summed total volume of the blended aggregates, the percent retained per sieve by volume can be determined for the blend. This is accomplished for a given sieve by dividing the volume retained on that sieve by the total volume of the blend. The following equation illustrates this calculation for the No. 4 (4.75 mm) sieve.

% Volume Retained on the No. 4 (4.75 mm) sieve = 12.20 / 36.93 = 33.04 %

6.12 Table 5 shows the percent retained by volume for each individual sieve and converts this to percent passing by volume. Percent passing by volume is calculated by subtracting the cumulative percent retained from 100.

Table 5

Sieve Size	Volume Retained per Sieve, cm^3	Percent Retained per Sieve	Cumulative Percent Retained	Percent Passing by Volume
1" (25 mm)	0.00	0.0	0.0	100
3/4" (19 mm)	0.57	1.54	1.54	98
1/2" (12.5 mm)	6.80	18.41	19.95	80
3/8" (9.5 mm)	6.78	18.36	38.31	62
# 4 (4.75 mm)	12.20	33.03	71.34	29
# 8 (2.36 mm)	2.94	6.26	77.96	22
# 16 (1.18 mm)	1.52	4.12	81.72	18
# 30 (0.60 mm)	0.76	2.06	83.78	16
# 50 (0.30 mm)	0.61	1.65	85.43	15
# 100 (0.15 mm)	0.77	2.09	87.52	12
# 200 (0.075 mm)	0.81	2.19	89.71	10
Pan (-0.075 mm)	3.80	10.29	100	0.0
Total (∑	36.93	100		

6.13 Next, compare the blend's percent passing by volume to the specifications. In Table 6, a typical 1-inch (25 mm) maximum aggregate size gradation is used.

Table 6

Sieve Size	25mm Maximum Gradation Band	Percent Passing by Volume
1" (25 mm)	100	100
3/4" (19 mm)	90-100	98
1/2" (12.5 mm)	50-74	80*
3/8" (9.5 mm)	25-60	62*
# 4 (4.75 mm)	20-28	29*
# 8 (2.36 mm)	16-24	22
# 16 (1.18 mm)	13-21	18
# 30 (0.60 mm)	12-18	16
# 50 (0.30 mm)	12-15	15
# 100 (0.15 mm)	8-15	12
# 200 (0.075 mm)	8-10	10.3*

6.14 The asterisks show the blend as too fine on four sieves. To correct this, remove 1 1/2 percent of the mineral filler and 20 percent of the fine aggregate (aggregate C), add 6 percent to the coarse aggregate (aggregate B) and 15 1/2 percent to the coarsest aggregate. Table 7 shows the results.

Stockpile	% Blend by Weight (Mass)
Aggregate A	45 ½
Aggregate B	36
Aggregate C	10
Mineral Filler	8 ½

Table 7

Sieve Size	Volume Retained per Sieve, cm^3	Percent Retained per Sieve	Cumulative Percent Retained	Percent Passing by Volume
1" (25 mm)	0.00	0.0	0.0	100
3/4" (19 mm)	0.87	2.30	2.30	98
1/2" (12.5 mm)	8.96	23.73	26.03	74
3/8" (9.5 mm)	7.76	20.55	46.58	53
# 4 (4.75 mm)	12.49	33.07	79.65	20
# 8 (2.36 mm)	1.67	4.42	84.07	16
# 16 (1.18 mm)	0.84	2.22	86.29	14
# 30 (0.60 mm)	0.36	0.95	87.24	13
# 50 (0.30 mm)	0.40	1.06	88.30	12
# 100 (0.15 mm)	0.65	1.72	90.02	10
# 200 (0.075 mm)	0.66	1.75	91.77	8.2
Pan (-0.075 mm)	3.11	8.23	100.00	0.0
Total (∑	37.77	100		

6.15 Table 8 shows the job mix formula by volume compared to the gradation band and the job mix formula percent passing by weight (mass).

Table 8

Sieve Size	25mm Maximum Gradation Band	Percent Passing by Volume	Percent Passing by Weight (Mass)
1" (25 mm)	100	100	100
3/4" (19 mm)	90-100	98	98
1/2" (12.5 mm)	50-74	74	74
3/8" (9.5 mm)	25-60	53	53
# 4 (4.75 mm)	20-28	20	20
# 8 (2.36 mm)	16-24	16	15*
# 16 (1.18 mm)	13-21	14	13
# 30 (0.60 mm)	12-18	13	12
# 50 (0.30 mm)	12-15	12	11*
# 100 (0.15 mm)	8-15	10	9
# 200 (0.075 mm)	8-10	8.2	7.6*

6.16 The percent passing by weight (mass) is used for mix design and job control. The asterisks show why computing percent passing by volume is needed for SMA mixes.

6.17 Voids in the Coarse Aggregate - Dry-Rodded Condition (VCA_{DRC}): Determine the VCA_{DRC} of the coarse aggregate fraction of the mix according to AASHTO T-19.

6.18 Since the gradation is a 1-inch (25 mm) maximum (3/4-inch or 19-mm nominal), the VCA_{DRC} was determined for aggregate retained on the No. 4 (4.75 mm) sieve. The sieve to use as the break point sieve is shown in Table 9. The break point is the sieve size that is used for the cut off when batching up the VCA sample for testing. For example, if the break point sieve is the #4, then the aggregates equal to or larger than the #4 sieve size would be used for the VCA testing. .

Table 9

Maximum Aggregate Size	Nominal Aggregate Size	Break Point Sieve
1 1/2" (37.2 mm)	1" (25 mm)	# 4 (4.75 mm)
1" (25 mm)	3/4" (19 mm)	# 4 (4.75 mm)
3/4" (19 mm)	1/2" 12.5 mm	# 4 (4.75 mm)
1/2" (12.5 mm)	3/8" (9.5 mm)	#8 (2.36 mm)
3/8" (9.5 mm)	# 4 (4.75 mm)	#16 (1.18 mm)

6.19 The calculation for VCA_{DRC} for the blend is shown below.

VCA_{DRC} = 100 * (Gca * γw - γs) / (Gca * γw)
VCA_{DRC} = 100 * (2.616 * 998 - 1610) / (2.616 * 998) = 38.33 %

Where
γs - unit weight of the dry rodded coarse aggregate fraction (kg/m^3)
γw - unit weight of water (998 kg/m^3)
Gca - bulk specific gravity of the coarse aggregate

6.20 Next, the percent VCA of the compacted mix (VCA_{MIX}) is calculated. The calculation for the percent VCA is shown below. A liquid asphalt binder content of 6.5 percent and a bulk specific gravity of 2.168 for the compacted specimens are used in this example.

Pbp = Ps * Pabp
Pbp = 93.5 * 0.80 = 74.8 %
VCA = 100 - Pbp * Gmb / Gca
VCA = 100 - 74.8 * 2.168 / 2.616 = 38.01, where

Pbp - percent (by weight [mass] total mix) aggregate retained on the breakpoint sieve (4.75 mm)
Ps - percent (by weight [mass] total mix) aggregate in the mix
Pabp - percent (by weight [mass] aggregate) aggregate retained on the breakpoint sieve (4.75 mm)
Gmb - bulk specific gravity of the compacted specimens
Gca - bulk specific gravity of the coarse aggregate

6.21 The VCA_{MIX} is compared to the VCA_{DRC}. The VCA_{MIX} is less than VCA_{DRC}, so this is a good mix because there is stone on stone contact.

$VCA_{MIX} = 38.01 < 38.33 = VCA_{DRC}$

7 Reporting

7.1 For Marshall designed mixes, report as required in ALDOT-307. For Superpave designed mixes, report as required in ALDOT-384.

7.2 In addition, include in the report the gradation by volume as compared to the gradation by weight (mass), the drain down results, and the comparison of the VCA_{MIX} to the VCA_{DRC}.